

Observational constraints on dark energy model

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The recent observations support that our Universe is flat and expanding with acceleration. We analyze a general class of quintessence models by using the recent type Ia supernova and the first year Wilkinson Microwave Anisotropy Probe (WMAP) observations. For a flat universe dominated by a dark energy with constant ω which is a special case of the general model, we find that $\Omega_{m0} = 0.30^{+0.06}_{-0.08}$ and $\omega_Q \leq -0.82$, and the turnaround redshift z_T when the universe switched from the deceleration phase to the acceleration phase is $z_T = 0.65$. For the general model, we find that $\Omega_{m0} \sim 0.3$, $\omega_{Q0} \sim -1.0$, $\beta \sim 0.5$ and $z_T \sim 0.67$. A model independent polynomial parameterization of dark energy is also considered, the best fit model gives $\Omega_{m0} = 0.40 \pm 0.14$, $\omega_{Q0} = -1.4$ and $z_T = 0.37$.

Keywords: Dark energy; quintessence; type Ia supernova.

1. Introduction

The type Ia supernova (SN Ia) observations indicate that the expansion of the Universe is speeding up rather than slowing down¹⁻⁴. The measurement of the anisotropy of the cosmic microwave background (CMB) favors a flat universe^{5,6,7}. The observation of type Ia supernova SN 1997ff at $z \sim 1.7$ also provides the evidence that the Universe is in the acceleration phase and was in the deceleration phase in the past^{4,8}. The transition from the deceleration phase to the acceleration phase happened around the redshift $z_T \sim 0.4$ ^{4,9}. In this paper, we use the notation z_T for the transition redshift. A new component with negative pressure widely referred as dark energy is usually introduced to explain the accelerating expansion. The simplest form of dark energy is the cosmological constant with the equation of state parameter $\omega_\Lambda = -1$. One easily generalizes the cosmological constant model to dynamical cosmological constant models such as the dark energy model with negative constant equation of state parameter $-1 \leq \omega_Q < -1/3$ and the holographic dark energy models¹⁰. If we remove the null energy condition restriction $\omega_Q \geq -1$ to allow supernegative $\omega_Q < -1$, then we have the phantom energy models¹¹. More exotic equation of state is also possible, such as the Chaplygin gas model with the equation of state $p = -A/\rho$ and the generalized Chaplygin gas model with the equation of state $p = -A/\rho^\alpha$ ¹². In general, a scalar field Q that slowly evolves down its potential $V(Q)$ takes the role of a dynamical cosmological constant. The scalar field Q is also called the quintessence field^{13,20}. The energy density of the

quintessence field must remain very small compared with that of radiation or matter at early epoches and evolves in a way that it started to dominate the universe around the redshift 0.4. Instead of the quintessence field with the usual kinetic term $\dot{Q}^2/2$, tachyon field as dark energy was also proposed²¹. The tachyon models have the accelerated phase followed by the decelerated phase.

Although most dark energy models are consistent with current observations, the nature of dark energy is still mysterious. Therefore it is also possible that the observations show a sign of the breakdown of the standard cosmology. Some alternative models to dark energy models were proposed along this line of reasoning. These models are motivated by extra dimensions. In these models, the usual Friedmann equation $H^2 = 8\pi G\rho/3$ is modified to a general form $H^2 = g(\rho)$ and the universe is composed of the ordinary matter only²²⁻²⁹. In other words, the dark energy component is unnecessary.

In this paper, I first use the 58 SN Ia data in Ref. 3, the 186 SN Ia data in Ref. 4 and WMAP data⁷ to constrain the parameter space of a general class of quintessence models discussed in Ref. 20. In that model, a general relation between the potential energy and the kinetic energy of the quintessence field was proposed. As we know, the average kinetic energy is the same as the average potential energy for a point mass in a harmonic oscillator. For a stable, self-gravitating, spherical distribution of equal mass objects, the total kinetic energy of the objects is equal to minus 1/2 times the total gravitational potential energy. Therefore, the physics of dark energy may be determined if the relationship between the potential energy and the kinetic energy is known. Then I consider three different model independent parameterizations of ω_Q to find out some properties of dark energy. After we determine the parameters in these models, the transition redshift z_T is obtained. The paper is organized as follows. After a brief introduction in section 1, the general class of models is reviewed in section 2. In section 3, I discuss the methodology used in this paper. In section 4, I give the main fitting results. In section 5, I conclude the paper by using a model independent analysis and compare the results with those in the literature.

2. Model Review

For a spatially flat, isotropic and homogeneous universe with both an ordinary pressureless dust matter and a minimally coupled scalar field Q source, the Friedmann equations are

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_m + \rho_Q), \quad (1)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + \rho_Q + 3p_Q), \quad (2)$$

$$\ddot{Q} + 3H\dot{Q} + V'(Q) = 0, \quad (3)$$

where dot means derivative with respect to time, $\rho_m = \rho_{m0}(a_0/a)^3$ is the matter energy density, a subscript 0 means the value of the variable at present time, $\rho_Q = \dot{Q}^2/2 + V(Q)$, $p_Q = \dot{Q}^2/2 - V(Q)$, $V'(Q) = dV(Q)/dQ$ and $V(Q)$ is the potential of the quintessence field. In Ref. 20, a general relationship

$$V(Q) = \beta \dot{Q}^2 + C, \quad (4)$$

was proposed instead of assuming a particular potential for the quintessence field or a particular form of the scale factor, where β and C are constants. Note that the above equation (4) is a constraint equation, one should not just substitute the above equation into the Lagrangian and thinks that the model is equivalent to a $1/2 + \beta$ kinetic term plus a cosmological constant term C . The above general potential includes the hyperbolic potential and the double exponential potential. In terms of ρ_{Q0} and ω_{Q0} , we have

$$C = \left[\frac{1}{2} - \beta - \left(\frac{1}{2} + \beta \right) \omega_{Q0} \right] \rho_{Q0}, \quad (5)$$

$$\rho_Q = (1/2 + \beta)(1 + \omega_{Q0})\rho_{Q0} \left(\frac{a_0}{a} \right)^{6/(2\beta+1)} + \left[\frac{1}{2} - \beta - \left(\frac{1}{2} + \beta \right) \omega_{Q0} \right] \rho_{Q0}, \quad (6)$$

$$p_Q = (1/2 - \beta)(1 + \omega_{Q0})\rho_{Q0} \left(\frac{a_0}{a} \right)^{6/(2\beta+1)} - \left[\frac{1}{2} - \beta - \left(\frac{1}{2} + \beta \right) \omega_{Q0} \right] \rho_{Q0}, \quad (7)$$

$$H^2 = \frac{8\pi G}{3} \left\{ \rho_{m0} \left(\frac{a_0}{a} \right)^3 + (1/2 + \beta)(1 + \omega_{Q0})\rho_{Q0} \left(\frac{a_0}{a} \right)^{6/(2\beta+1)} + C \right\}. \quad (8)$$

To make the quintessence field sub-dominated during early times, we require that $\beta \geq 0.5$. The transition from deceleration to acceleration happens when the deceleration parameter $q = -\ddot{a}H^2/a = 0$. From equations (2), (6) and (7), in terms of the redshift parameter $1 + z = a_0/a$, we have

$$(1 + z_T)^3 + 2(1 - \beta)(1 + \omega_{Q0}) \frac{\rho_{Q0}}{\rho_{m0}} (1 + z_T)^{6/(2\beta+1)} - [1 - 2\beta - (1 + 2\beta)\omega_{Q0}] \frac{\rho_{Q0}}{\rho_{m0}} = 0. \quad (9)$$

This equation gives a relationship between ω_{Q0} and Ω_{Q0} . Now let us turn our attention to two special cases.

Case 1: $C = 0$, the equation of state of the scalar field is a constant, $\omega_Q = (1/2 - \beta)/(1/2 + \beta)$. The potential is ^{17,18}

$$V(Q) = A[\sinh k(Q/\alpha + B)]^{-\alpha},$$

where $\alpha = 2/(\beta - 1/2)$, $k^2 = 48\pi G/(2\beta + 1)$, $A^{\beta-1/2} = (1/2 + \beta)C_2^{2\beta+1}\beta^{\beta-1/2}/(\rho_{m0}a_0^3)$ and B is an arbitrary integration constant.

Case 2: $\beta = 1/2$, the pressure of the scalar field becomes a constant $p_Q = -C = \omega_{Q0}\rho_{Q0}$ and the potential is the double exponential potential ¹⁹

$$V(Q) = \frac{A^2}{8}[\exp(2\alpha Q) + \exp(-2\alpha Q)] + \frac{\alpha^2 A^2}{6\pi G} - \frac{A^2}{4}.$$

The constant pressure model is equivalent to an ordinary matter with effective matter content $\Omega_{m0}^{\text{eff}} = (1 + \omega_{Q0})\Omega_{Q0} + \Omega_{m0}$ plus a cosmological constant $\rho_\Lambda = -\omega_{Q0}\rho_{Q0}$.

3. Methodology

In order to use the WMAP result, one usually parameterizes the location of the m -th peak of CMB power spectrum as ³⁰

$$l_m = (m - \phi_m)l_A,$$

where the acoustic scale l_A is

$$l_A = \frac{\pi}{\bar{c}_s} \frac{\tau_0 - \tau_{ls}}{\tau_{ls}} = \frac{\pi}{\bar{c}_s} \frac{\int_0^{z_{ls}} dz / \sqrt{g(z)}}{\int_{z_{ls}}^{\infty} dz / \sqrt{g(z)}}, \quad (10)$$

the conformal time at the last scattering τ_{ls} and at today τ_0 are

$$\tau_{ls} = \int_0^{\tau_{ls}} d\tau = \int_{z_{ls}}^{\infty} \frac{dz}{a_0 H_0 \sqrt{g(z)}}, \quad (11)$$

$$\tau_0 = \int_0^{\tau_0} d\tau = \int_0^{\infty} \frac{dz}{a_0 H_0 \sqrt{g(z)}}, \quad (12)$$

$$g(z) = \Omega_{m0}(1+z)^3 + \Omega_{r0}(1+z)^4 + (1/2 + \beta)(1 + \omega_{Q0})\Omega_{Q0}(1+z)^{6/(2\beta+1)} \\ + \left[\frac{1}{2} - \beta - \left(\frac{1}{2} + \beta \right) \omega_{Q0} \right] \Omega_{Q0}, \quad (13)$$

$\Omega_{r0} = 8.35 \times 10^{-5}$ is the current radiation component and $z_{ls} = 1089 \pm 1$ ⁶. The difficulty of this method is that there are several undetermined parameters, such as ϕ_m and \bar{c}_s . Instead, we use the CMB shift parameter $\mathcal{R} \equiv \Omega_{m0}^{1/2} a_0 H_0 (\tau_0 - \tau_{ls}) = 1.716 \pm 0.062$ ³¹ to constrain the model.

The luminosity distance d_L is defined as

$$d_L(z) = a_0 c (1+z) \int_t^{t_0} \frac{dt'}{a(t')} = c \frac{1+z}{H_0} \int_0^z du [g(u)]^{-1/2}. \quad (14)$$

The apparent magnitude redshift relation becomes

$$m(z) = M + 5 \log_{10} d_L(z) + 25 = \mathcal{M} + 5 \log_{10} \mathcal{D}_L(z) \\ = \mathcal{M} + 5 \log_{10} \left[c(1+z) \int_0^z du [g(u)]^{-1/2} \right], \quad (15)$$

where $\mathcal{D}_L(z) = H_0 d_L(z)$ is the "Hubble-constant-free" luminosity distance, M is the absolute peak magnitude and $\mathcal{M} = M - 5 \log_{10} H_0 + 25$. \mathcal{M} can be determined from the low redshift limit at where $\mathcal{D}_L(z) = z$. We use the 54 SNe Ia data with both the stretch correction and the host-galaxy extinction correction, i.e., the fit 3 supernova data in Ref. 3 (we refer the data as Knop sample), and the 186 SNe Ia data in Ref. 4 (we refer the data as Riess sample) to constrain the model. The parameters in the model are determined using a χ^2 -minimization procedure based on MINUIT code. There are four parameters in the fit: the current mass density Ω_{m0} , the current dark energy equation of state parameter ω_{Q0} , the constant β as well as the nuisance parameter \mathcal{M} . The range of parameter space is $\Omega_{m0} = [0, 1]$ and $\omega_{Q0} = (-1, 0]$.

4. Results

For the dark energy model with constant ω_Q , i.e., the model with $C = 0$, the best fit parameters to the 54 knop sample are $\Omega_{m0} = [0, 0.46]$ centered at 0.30 and $\omega_Q = (-1.0, -0.44]$ centered at almost -1.0 with $\chi^2 = 45.6$ at 68% confidence level. The best fit parameters to the 157 Riess gold sample are $\Omega_{m0} = [0.19, 0.37]$ centered at 0.31 and $\omega_Q = (-1, -0.75]$ centered at almost -1.0 with $\chi^2 = 177.1$ at 68% confidence level. The best fit parameters to the 186 Riess gold and silver sample are $\Omega_{m0} = [0.22, 0.36]$ centered at 0.30 and $\omega_Q = (-1, -0.81]$ centered at almost -1.0 with $\chi^2 = 232.3$ at 68% confidence level. The best fit parameters to the Riess gold sample and WMAP data combined are $\Omega_{m0} = [0.22, 0.36]$ centered at 0.30 and $\omega_Q = (-1.0, -0.81]$ centered at almost -1.0 with $\chi^2 = 177.3$ at 68% confidence level. The best fit parameters to the Riess gold and silver sample and WMAP data combined are $\Omega_{m0} = [0.23, 0.35]$ centered at 0.30 and $\omega_Q = (-1.0, -0.84]$ centered at almost -1.0 with $\chi^2 = 232.4$ at 68% confidence level. From the above results, it is shown that the addition of Riess silver data give almost the same results as those from Riess gold sample only. Therefore, we will use Riess gold sample only in the following discussion. The confidence regions of Ω_{m0} and ω_Q are shown in figure 1.

For the general model $C \neq 0$, we first analyze the special constant pressure model $\beta = 1/2$ which is equivalent to the Λ -CDM model. The best fits to the 54 Knop sample are $\Omega_{m0} = [0, 0.46]$ centered at almost zero and $\omega_{Q0} = (-1, -0.54]$ centered at -0.71 with $\chi^2 = 45.6$ at 68% confidence level. The best fits to the 157 Riess gold sample are: $0 \leq \Omega_{m0} \leq 0.37$ and $-1 < \omega_{Q0} \leq -0.63$ at 68% confidence level with $\chi^2 = 177.1$. Note that the effective $\Omega_{m0} \sim 0.3$ although the best fit Ω_{m0} is almost zero. The best fits to the 157 Riess gold sample and WMAP data combined are: $0.25 \leq \Omega_{m0} \leq 0.35$ and $-1 < \omega_{Q0} \leq -0.93$ with $\chi^2 = 177.1$ at 68% confidence level. The confidence regions of Ω_{m0} and ω_{Q0} are shown in figures 2 and 3.

For the general model, the range of parameter space is $\Omega_{m0} = [0, 1]$, $\omega_{Q0} = (-1, 0]$ and $\beta \geq 0.5$. The best fits to the 54 Knop sample are: $0 \leq \Omega_{m0} \leq 0.50$, $-1 < \omega_{Q0} \leq -0.23$ and β varies in a big range with $\chi^2 = 45.6$ at 68% confidence level. The best fits to the 157 Riess gold sample are: $0 \leq \Omega_{m0} \leq 0.38$, $-1 < \omega_{Q0} \leq -0.57$ and β varies in a big range with $\chi^2 = 177.1$ at 68% confidence level. The best fits to the 157 Riess gold sample and WMAP data combined are: $0.21 \leq \Omega_{m0} \leq 0.37$, $-1.0 < \omega_{Q0} \leq -0.75$ and $\beta \geq 0.5$ with $\chi^2 = 177.1$ at 68% confidence level. From the above results, we see that the best fit model tends to be the Λ -CDM model with $\Omega_{m0} \sim 0.3$.

5. Model-independent Results

To construct a model independent result, we first parameterize the dark energy density by two parameters ³², $\Omega_Q(z) = A_0 + A_1(1+z) + A_2(1+z)^2$, here $\Omega_Q(z) = 8\pi G\rho_Q(z)/(3H_0^2)$ and $A_0 = 1 - \Omega_{m0} - \Omega_{r0} - A_1 - A_2$. The relationship between the

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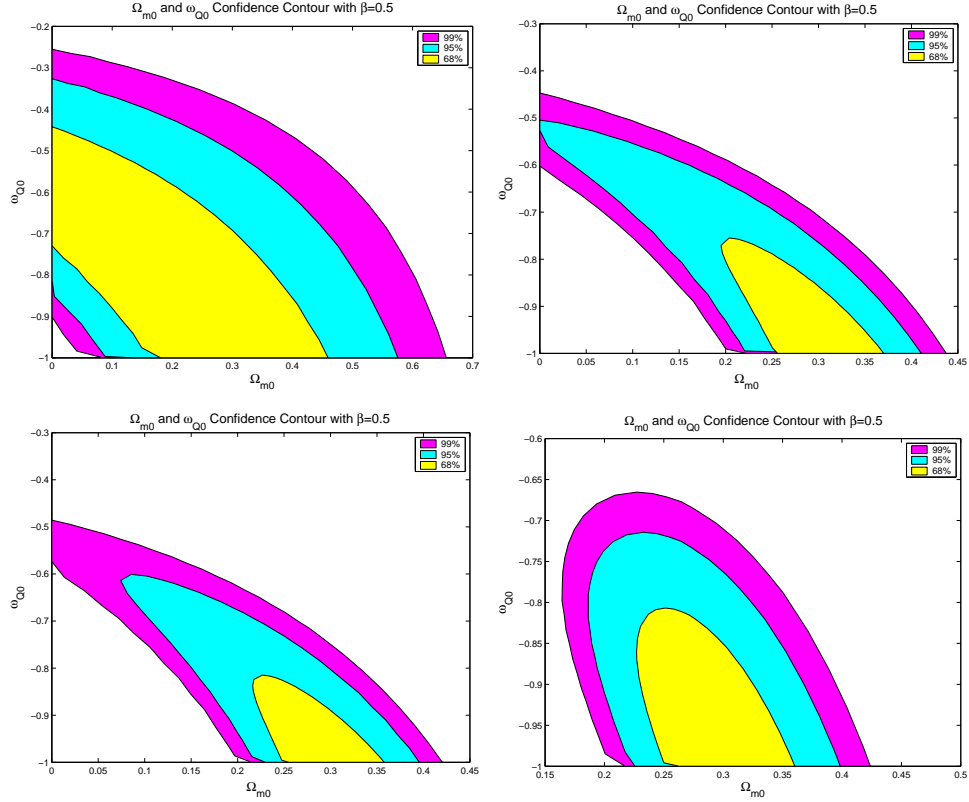


Fig. 1. The confidence contours of Ω_{m0} and ω_Q for the $C = 0$ model. The left upper panel is the 68%, 95% and 99% confidence regions fitted from Knop sample. The right upper panel is the 68%, 95%, 99% confidence regions fitted from Riess gold sample, the left lower panel is the 68%, 95% and 99% confidence regions fitted from Riess gold and silver sample. The right lower panel is the 68%, 95%, 99% confidence regions fitted from Riess gold sample and WMAP data.

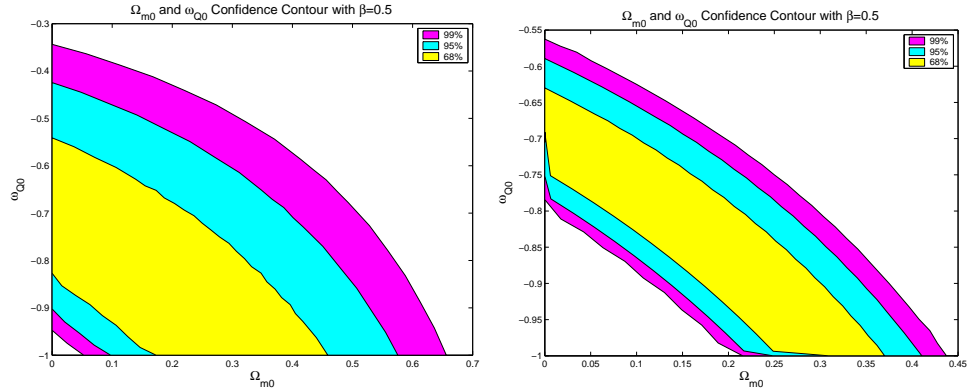


Fig. 2. The 68%, 95% and 99% confidence contours of Ω_{m0} and ω_{Q0} for $\beta = 1/2$. The left panel shows fits to Knop sample and the right panel shows fits to Riess gold sample.

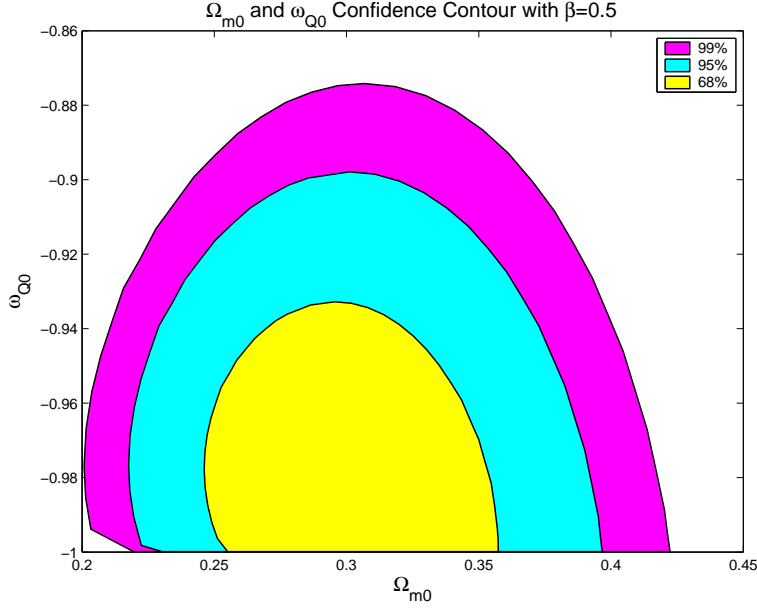


Fig. 3. The 68%, 95% and 99% confidence contours of Ω_{m0} and ω_{Q0} for $\beta = 1/2$ with Riess gold sample and WMAP data.

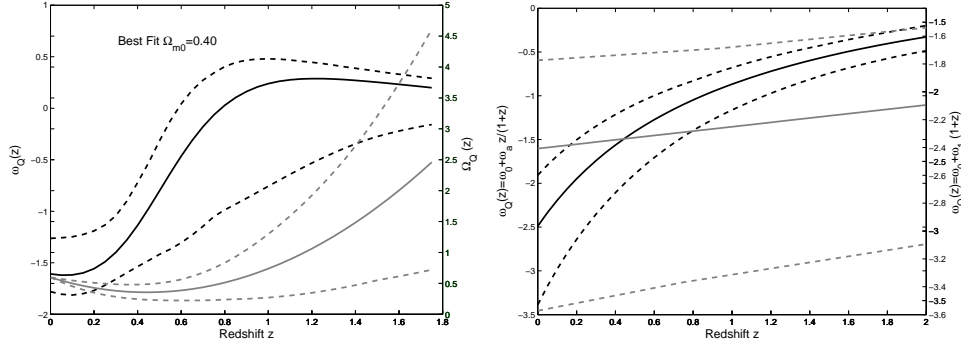


Fig. 4. The best supernova and WMAP data fits to the polynomial model and linear model. The left panel shows Riess gold sample and WMAP data fits to the two parameter polynomial model, the light black lines are for Ω_Q and the dark black lines for ω_Q , the solid lines are from the best fit. The right panel shows Riess gold sample and WMAP data fits to the two parameter linear model of ω_Q , the solid lines are from the best fit, the light black lines are for the linear model and the dark black lines are for the stable model. The dashed lines define the 1σ boundaries.

dark energy state of equation parameter ω_Q and the redshift is

$$\omega_Q = \frac{1+z}{3} \frac{A_1 + 2A_2(1+z)}{A_0 + A_1(1+z) + A_2(1+z)^2} - 1.$$

With the above parameterization, we find that $\Omega_Q \ll \Omega_m$ and $\omega_Q \approx -1/3$ when $z \gg 1$. The best fit parameters to Riess gold sample and WMAP data are $\Omega_{m0} =$

0.40 ± 0.14 , $A_1 = -3.6^{+3.8}_{-4.6}$ and $A_2 = 1.23^{+1.74}_{-1.23}$ with $\chi^2 = 174.3$. By using the best fit parameters, we find that $\omega_{Q0} = -1.4$ and $z_T = 0.37$. Then we consider the commonly used two parameter linear model $\omega_Q(z) = \omega_0 + \omega_1(1+z)$. The Riess gold sample and WMAP data give that $\Omega_{m0} = 0.49^{+0.09}_{-0.20}$, $\omega_0 = -2.57^{+1.58}_{-5.18}$ and $\omega_1 = 0.16^{+0.53}_{-0.16}$ with $\chi^2 = 173.7$. Combining the best fit parameters, it is found that $\omega_{Q0} = -2.41$ and $z_T = 0.29$. Because the above linear model is divergent as $z \gg 1$, so we next consider a more stable parameterization of $\omega_Q(z) = \omega_0 + \omega_a z/(1+z)$ ³³. By using this parameterization, we find that the best fit parameters to Riess gold sample and WMAP data are $\Omega_{m0} = 0.47^{+0.10}_{-0.19}$, $\omega_0 = -2.5^{+1.5}_{-4.9}$ and $\omega_a = 3.2^{+6.6}_{-3.2}$ with $\chi^2 = 173.5$. Therefore the turnaround redshift is $z_T = 0.28$ and $\omega_{Q0} = -2.5$. Note that the cosmological constant model $\omega_0 = -1$ and $\omega_a = 0$ is at the boundary of the 1σ parameter space. However, the dark energy term became the dominant term when $z \gg 1$ since $\omega_0 + \omega_a = 0.7$. Therefore, we use the results from the polynomial parameterization only. The evolutions of $\Omega_Q(z)$ and $\omega_Q(z)$ with redshift are shown in figure 4.

For the model independent second order polynomial parameterization, we find that $\Omega_{m0} = 0.40 \pm 0.14$, $\omega_{Q0} = -1.4$ and $z_T = 0.37$. Alam, Sahni and Starobinsky obtained $\Omega_{m0} = 0.385$ and $z_T = 0.39 \pm 0.03$ in a similar analysis ³². Tegmark *et al.* found that $\Omega_{m0} \approx 0.30 \pm 0.04$ by using the WMAP data in combination with the Sloan Digital Sky Survey (SDSS) data ³⁴. More recently, Riess *et al.* showed that $z_T = 0.46 \pm 0.13$ from the two parameter linear model by using SNe Ia data only with the assumption that $\Omega_{m0} = 0.27 \pm 0.04$ ⁴. The above results are consistent with each other. For a flat universe with constant ω_Q , we find that $\Omega_{m0} = 0.30^{+0.06}_{-0.08}$ and $\omega_Q \leq -0.82$. The result is consistent with our model independent results and that in Refs. 3, 4, 35. With those parameter values, we find that the turnaround redshift $0.47 \leq z_T \leq 0.95$. For the constant pressure model $\beta = 1/2$, the best fits to the combined supernova and WMAP data are $\Omega_{m0} = 0.298$ and $\omega_{Q0} = -0.985$ which result in $z_T = 0.65$. The best parameter fits to the combined supernova and WMAP data for the general model analyzed in this paper are $\Omega_{m0} \sim 0.3$, $\omega_{Q0} \sim -1.0$ and $\beta \sim 0.5$. The turnaround redshift is $z_T \sim 0.67$. These results are consistent with the observations. In conclusion, it is shown that the general model in Ref. 20 is consistent with current observations and the model effectively tends to be the Λ -CDM model. Furthermore, our model independent results support the conclusion of dark energy metamorphosis obtained in Ref. 32.

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